ARMY RESEARCH LABORATORY

Proof-Testing the Physics Applications Inc. 50-mm Laboratory Gun

by Graham F. Silsby

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Abstract

Reported here is the effort to proof-test a newly acquired breech-end assembly for the 50-mm high-pressure powder gun for terminal ballistic testing in the U.S. Army Research Laboratory's (ARL) Range 309A (R309A). The performance of a custom-produced 0.012-inch web 7-perforation M30 propellant in routine use there was modeled by the ARL-developed one-dimensional (1-D) interior ballistic code IBHVG2 to select a propelling charge mass (CM) that would produce a pressure of approximately 130 ksi for the purpose of proof-testing the gun. Proof slugs of the appropriate mass, 900 g, were fabricated. The breech end was assembled to a scrap 0.6-m piece of barrel to add mass, mounted in a hastily built fixture, and fired without recoil system at ARL's barricaded Range 18. The priming system and recipe supplied with the Physics Applications Inc. (PAI) breech end was adjusted until a pressure-time (P-T) curve with acceptably low-peak negative differential pressures was obtained. This required reducing the propellant in the 0.50-cal. case used as a primer and putting Benite strands in the spit tube.

Following establishment of a suitable priming recipe, the pressure was raised from 50 ksi to 120 ksi in steps, resulting in slight, permanent plastic deformation of the chamber and inducing a favorable state of residual stress (autofrettage). The assembly was nondestructively examined for cracks before and after the proof-test procedure, and no reportable indications were found. This report briefly describes the hardware, the rationale behind the proof-test, the mechanical response of the system, the interior ballistics, and the results. Extensive instrumentation was used during the tests, and the results are tabulated and plotted.

Acknowledgments

A number of people made significant contributions to this effort to qualify the Physics Applications Inc. (PAI), breech-end hardware for service with the 50-mm gun system in the U.S. Army Research Laboratory's (ARL) Range 309A. The original 50-mm gun was acquired from the University of Dayton Research Institute (UDRI) more than 10 yr ago and had recently experienced a number of breech-obturation failures. Hal Swift, Dave Strange, and Jerry Streithorst of PAI provided much valuable support and counsel in overcoming these problems, removing the immediate pressure to place the PAI breech end into service. They also provided insight into the priming and propelling charge design as supplied by PAI, which was driven by the necessity of using commercially available propellants.

Richard Fararra, a metallurgist and expert on fracture mechanics at the U.S. Army Research and Development Center at Watervliet Arsenal, was of invaluable assistance in resolving heat-treatment problems in consultation with the PAI personnel. In addition, he independently performed the proof-stress residual-strain calculations as a check on our numbers. His fracture mechanics analysis for us, predicting critical crack depth, failure mode, and estimated fatigue life, was also greatly appreciated.

Bill Edmanson and Melissa Klusewitz of Range 309A, Carl Ruth of ARL's Propulsion and Flight Division (PFD), and Davey Hewitt and James Tuerk of PFD's Range 18 did the work reported here in a timely and capable fashion. They took the interruptions necessitated by the initial priming problems in stride. Scott Walton and Dan Bullock of PFD calibrated the piezoelectric pressure gauges used in this effort. PFD's George Keller and Lang Mann Chang repeatedly took time out from their own work to assure that we overcame our initial priming problems quickly. The ARL machine shop personnel were, as usual, very helpful both in figuring out ways to quickly overcome hardware problems and in rapidly fabricating needed prototypes. PFD's Ron Anderson was quite patient as he helped us acquire the experience needed to become comfortable with the ARL interior ballistics code IBHVG2, used to determine the appropriate propelling charges to use for

proof-testing. Many other people provided peripheral support and are acknowledged here without mentioning names.

Finally, thanks go out to my branch chief, William de Rosset, and to PFD's Arpad Juhasz for their careful review of the report draft, which was necessary with this author to keep the reader from sometimes being swamped in a sea of ambiguous verbosity.

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1. Introduction

Reported here are the results of a program to proof-test the new Physics Applications Inc. (PAI), breech-end hardware and 1-m wear section for the 50-mm smooth-bore gun system in the Terminal Effects Division's (TED) Range 309A. Nine shots were used to develop an acceptable priming recipe, three to step up in pressure to the desired proof-test pressure, and two post-proof shakeout shots as part of the planned procedure. A final shot to destroy surplus propellant again explored the priming. This report discusses the hardware, priming development, proof-test procedure, interior ballistics results, and general observations.

The parts were initially given a thorough nondestructive examination (NDE) for cracks at the Aberdeen Proving Ground's Weapons Processing Section of the Aberdeen Test Center (ATC), and none was found. The inspection method could reliably detect a closed half-penny crack of about 2-mm depth. See any reference on machine design for an introductory discussion of fracture mechanics. The proofing was conducted as a high-risk test at the Propulsion and Flight Division's (PFD)* Range 18 Barricade A, with personnel and equipment protected against a gun explosion or other catastrophic event.

The intended proof-test procedure was to start with a main propelling charge mass (CM) giving approximately 350 MPa (50 ksi) and establish the appropriate priming CM to be used in the 0.50-cal. cartridge case serving as a primer. Starting with the supplier's recommendation, the priming charge would be raised or lowered as indicated by performance.

An interior ballistic code, IBHVG2 [1], was used to provide an estimate of CM vs. breech pressure and muzzle velocity. To perform the modeling, the chamber volume was determined by volumetric means with the initial U.S. Army Research Laboratory (ARL) igniter (spit) tube used (discussed later) and the empty PAI 0.50-cal. case unprimed. Chamber volume was 2,120 cm^3, bore diameter was 50.50 mm (1.988 inches), and length of travel used was 1.6 m. The results indicated

* PFD became the Ballistics and Weapons Concepts Division on 18 January 1998.

that a very high in-bore mass was needed, along with a very small web-size propellant. An undeterred seven-perforation cylindrical M30 propellant with a nominal web size of 0.30 mm (0.012 inch) was selected, which had earlier been custom-made for interior ballistics studies and for routine use in our medium-caliber laboratory gun systems. Two lots, RAD-PE-771-4 and RAD-E-29, were used. For an in-bore mass of 900 g, the initial CM needed would be 750 g.

The interior ballistic performance was monitored for unusual behavior by the use of piezoelectric pressure gauges at the breech face and chamber throat. Pressure waves observed on the first shots were not mitigated by varying the priming charge (one shot each at 8 g and at 16 g). This state of affairs necessitated doing additional shots to develop a safe and reliable priming train design.

The propelling charge was then to be increased in 20-ksi steps through the pressure needed to cause the chamber and bore wall to yield (approximately 90 ksi) and increase the pressure beyond that to about 130 ksi, inspecting for cracks, for chamber growth, and for other trouble after each shot. A shot at approximately 90 ksi and a final shot at nominally 45 ksi, each followed by measurement and visual inspection, completed the proof-firings. A shot duplicating the initial priming load was fired with the PAI igniter tube, but filled with Benite (13 g), to see what improvement could be expected by this approach using the hardware supplied.

The gun was then disassembled and submitted for NDE again. No detectable flaws were found with the exception of moderate heat checking of the bore wall at the breech end, extending onto the rear face of the tube.

2. Hardware, Loading Geometry, and Instrumentation

The PAI breech-end assembly consists of a powder chamber, a charge plate (breech plate or obturating plate), a breech plug that is chambered for the 0.50-cal. cartridge for the M2 machine gun, and a cap breech with integral firing solenoid assembly. A large threaded ring and nut attaches the chamber to a 1-m wear section of launch tube (see Figure 1). The wear section serves to adapt the PAI breech to our current barrel assembly, which was supplied earlier by the University of Dayton

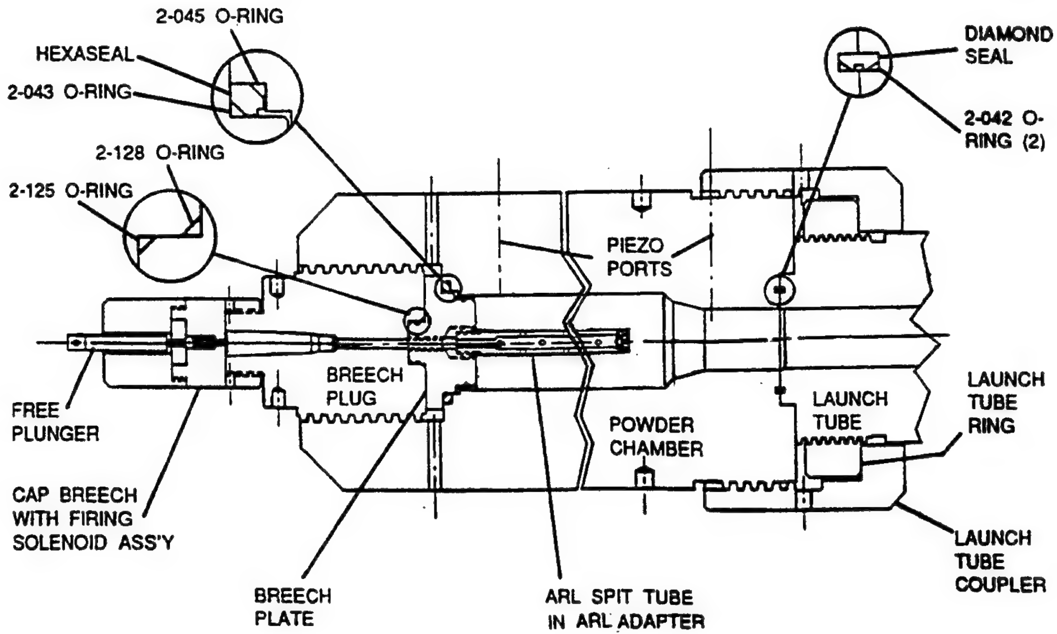

Figure 1. PAI Breech-End Hardware (Overview). (A spit tube of ARL design having a smaller outside diameter [OD] can replace the PAI spit tube to permit the use of military M11 copper crusher [CC] gauges as a backup to the piezoelectric gauges.)

Research Institute (UDRI). The priming train geometry varied during the program, with a series of U.S. Army Ballistic Research Laboratory (BRL)-designed* igniter tubes of smaller OD replacing the larger-diameter PAI spit during part of the program. The propelling charge is contained in a kraft paper tube wrapped on a boss on the charge-holding plate. With small propelling CMs, it is necessary to extend the charge along the spit tube, so a closed-cell polyethylene foam liner is dropped into the kraft cylinder before loading. Additional propellant can be loaded up the gun bore in thin-walled polyethylene bags, if needed (see Figure 2).

For proof-testing the system, a 600-mm-long piece of worn-out UDRI barrel was attached to the PAI breech-end assembly to mate with the UDRI recoil system. The recoil system consists of a thrust ring at the muzzle that engages, through hydraulic snubbers, a bracket attached to the support rail by means of another bracket. The entire barrel assembly rested on appropriate roller mounts on

* BRL was deactivated on 30 September 1992 and subsequently became a part of ARL on 1 October 1992.

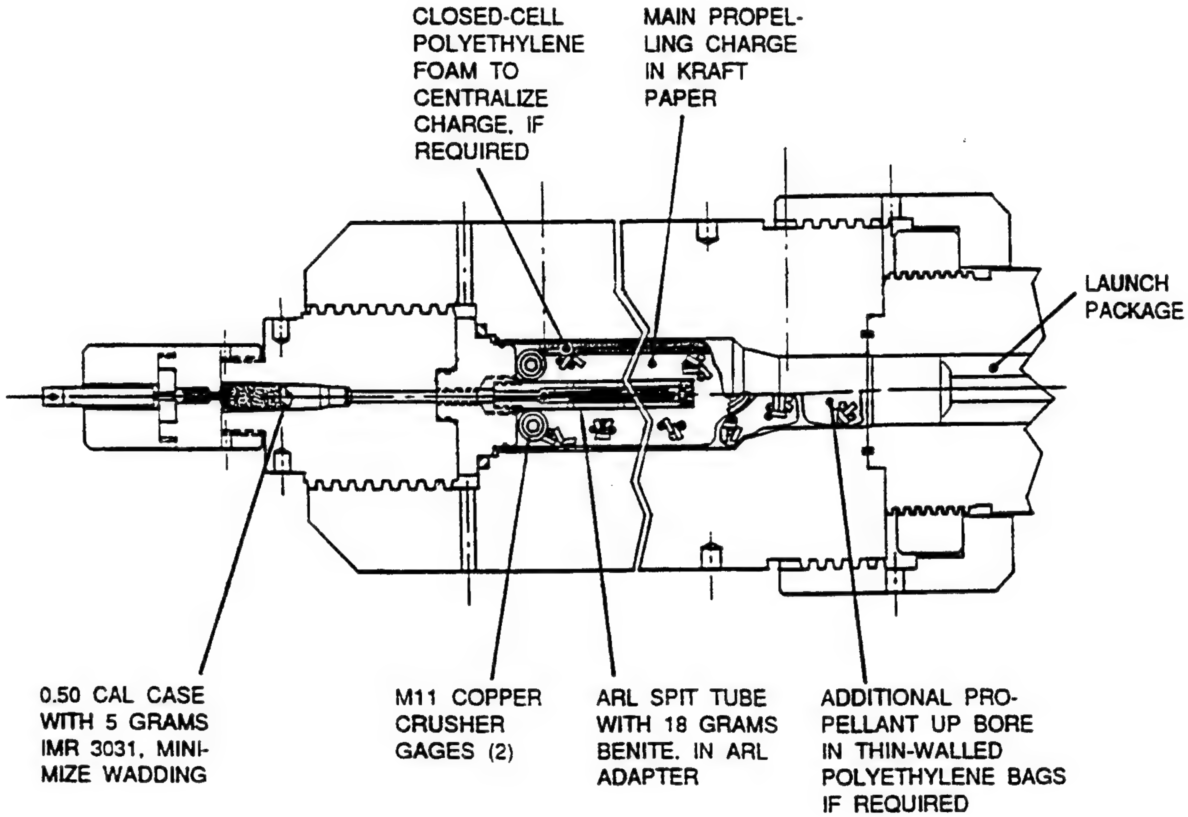

Figure 2. Ignition and Propelling Charge Geometry.

the rail. The chamber was supported by a simple purpose-built roller carriage. An extension on the rail rear accepts the hydraulic ramming system. The front end of the rail assembly was fitted with outriggers for lateral stability.

At the beginning of the firing program, for site-specific safety reasons, it was decided to elevate the trajectory. Nominally 12-inch-square timbers were placed under the beam supporting the outriggers. The rear mounting block of the rail assembly and the timbers rested on steel plate that covered the concrete pad in the barricade (see Figure 3).

The assembly was quite massive and was not attached to the plate. On firing, the muzzle end of the assembly would buck upward, exerting considerable vertical force on the ball transfer bearings

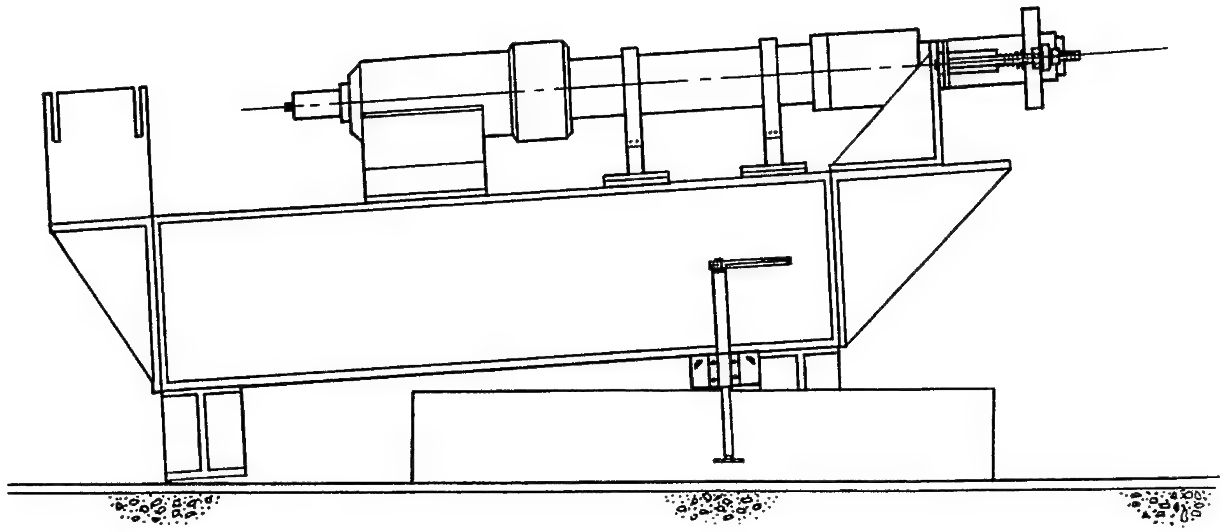

Figure 3. Gun Configuration for Proof-Firing.

that supported the chamber and, thereby, damaging them. (This is not expected to be a problem in the range, where the gun rail is bolted down and the barrel and chamber supports are designed to provide constraint against vertical motion.) The mounting rail assembly would slide about 0.3 m rearward on each shot and would be returned to the original position prior to the next shot.

The proof slugs were assemblies of 1 1/2-inch diameter steel and/or brass slugs in carriers of polycarbonate and/or Polypropylux 944A (TM) (a proprietary polypropylene-based plastic from Westlake Plastics, Lenni, PA) (see Figure 4). The knife-edge seal on the base has been used for a long time with the UDRI 50-mm gun. Because of its geometry, it should be a self-energizing design. However, there had been no way to test this hypothesis during the course of routine operations. Gas leakage up the bore during early proof shots indicated that the knife-edge feature on the shot base was not effective, and the lips were machined blunt. No change in projectile obturation was noticed. Perhaps the seemingly light bore wear after the first few shots was enough to cause loss of obturation, though the wear manifested itself only as a visible frosting of the originally shiny 20-μinch honed finish.

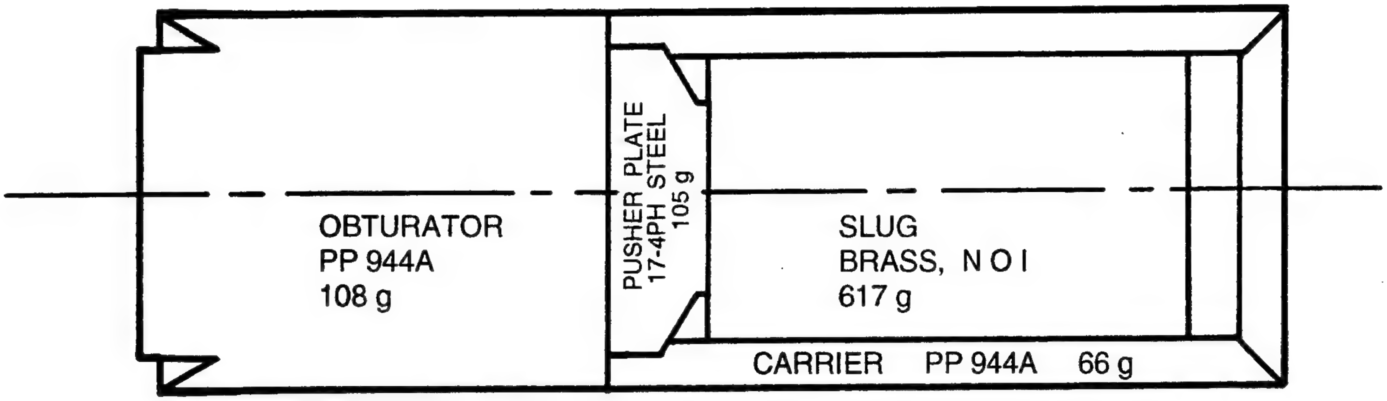

Figure 4. Typical Proof Slug. (Shot TED07, shown in cross section. Design varies. Material on hand was used as ballast to adjust mass. For example, scrap nonstandard pusher plate shown was used as ballast and is not necessary to launch the 1.5-inch-diameter slug.)

Velocity was first measured by down-bore Doppler radar. When projectile obturation problems caused repeated loss of signal, a Weibel-radar setup looking downrange was added. The strength of the returned signal from the Weibel radar was very low, so that the position of the projectile on each return could not be readily discerned from the background. The scatter in the velocity data (to be discussed later) reflects the low credibility of the Weibel velocities.

Pressure was measured by two means. Piezoelectric gauges provided pressure-time (P-T) records at the chamber's breech face and start of the bore. In addition to the two piezo gauges in the chamber, one piezo gauge was installed in the middle of the PAI wear section and one piezo gauge near the muzzle in the UDRI extension. The Kistler 607C4 piezo gauges normally used with the 50-mm gun were used in the proof-testing for economic reasons. They were calibrated before and after the proof-test and showed no ill effect. The gauges were removed prior to each shot, and the ports were filled with silicone grease to protect the gauge sensor surface from high temperature. The accuracy of the gauges is guaranteed through about 700 MPa (100 ksi), so pressures above this value are advisory only [2].

In addition, two M11 internal CC gauges were located at the base of the main propelling charge. These are cylindrical assemblies about the size of the last segment of a person's thumb. CC gauges are used as a backup, measuring only peak pressure. A piston of known area is exposed to the pressure and bears on a BB-sized copper ball. The pressure crushes it between the piston and an anvil. After the shot, the crushed height is read and the corresponding pressure picked off a calibration sheet for the lot of balls used. The only specialized instrumentation that is desirable is a micrometer that reads to 0.0001 inch or 0.0025 mm, which correspond to the least count on the calibration sheet supplied.

In use, the CC gauges are placed at the base of the propelling charge. When the propellant burns properly and the shot starts to move, a forward pressure gradient is established. Since there is theoretically no gas flow at the breech face, the CCs experience little force to project them downrange. After a shot, they are usually recovered in the chamber or the breech end of the barrel. They are disassembled, and the peak breech pressure is read.

The highest-pressure internal gauges have one drawback: the external pressure elastically deforms the barrel of the gauge inward. Though the M11 CC gauge calibration table goes to 111 ksi (765 MPa), friction on the piston results in erroneously low readings once 90–100 ksi is exceeded [3]. Usually, a pair of CC gauges is used for redundancy, and the higher of the two pressures is reported for this reason. Indeed, on the higher pressure shots, the CC pressures were under those measured by the piezoelectric gauges.

To accommodate the two M11 CC gauges, the 15/16-inch-OD PAI-supplied igniter tube was replaced by a 3/4-inch-OD brass igniter tube of long-standing design and a custom adapter. In the course of developing the priming system, a new 3/4-inch-OD igniter tube was made and tried with two spit-hole patterns. The various igniter tube geometries are compared in Figure 5.

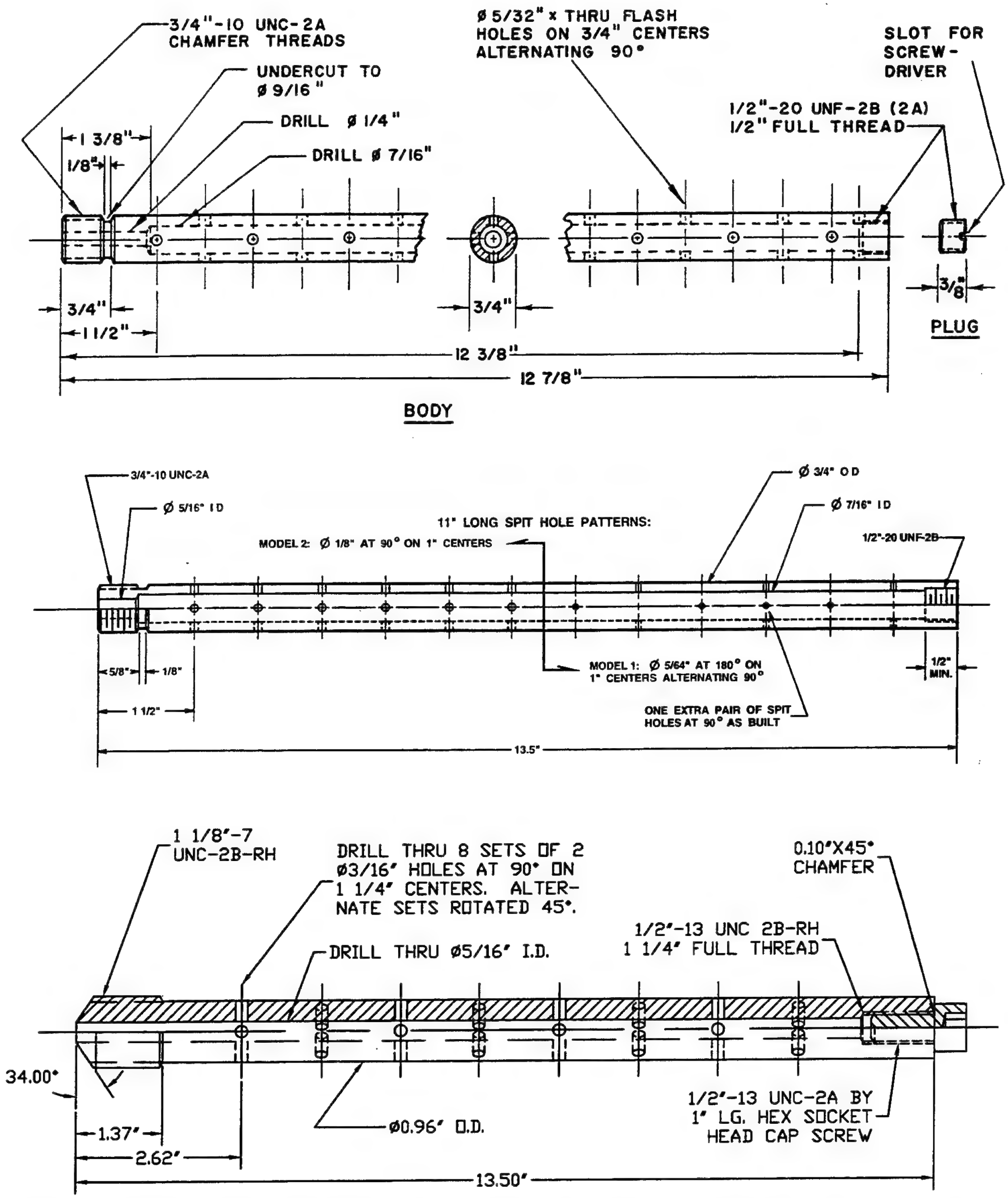

Figure 5. Igniter Tubes Compared. (Top: Original ARL spit tube tried, traditionally used with the UDRI 50-mm gun in Range 309A. Middle: Custom ARL spit tubes, Models 1 and 2. Bottom: Original PAI igniter tube tried with Benite on last shot.)

3. Priming Development

The 750-g CM was first loaded to the full diameter of the paper cartridge formed on the charge plate, coming to 50 mm below the tip of the igniter tube. The initial priming charge was 12 g of Improved Military Rifle (IMR) 3031 rifle propellant (lot P-71-JU1OC 1294). (Full capacity of the 0.50-cal. case was measured to be 16.5 g.) This resulted in an unacceptable pressure wave. Eight and 16 g were worse (see Figure 6). The 16-g charge blew the igniter tube away and also overpressured the 0.50-cal cartridge case, as evidenced by its sticking in the chamber and by the flattening of its head-stamping. The full data on these and subsequent shots are tabulated in the Appendix.

Some tweaking of the priming had been expected, but the nasty P-T traces forced a halt to testing until the problem could be resolved. Advice was sought from PFD's George Keller and Lang Mann Chang, ignition experts. They agreed that a foam liner should be used to centralize the charge. This was accomplished through the use of 5-mm-thick closed-cell polyethylene packaging foam sheet placed inside the full length of the paper cartridge. This brought the charge to the full length of the 3 1/4-inch (83 mm) inside-diameter (ID) portion of the chamber (see Figure 7). With 12 g of priming charge, the pressure waves were much reduced (−26 MPa maximum negative pressure difference vs. −69 MPa without the liner under the same priming conditions) (see Figure 8).

The P-T curves were still troublesome, so at the advice of Dr. Chang, Benite was tried in the igniter tube. Benite is a black powder-nitrocellulose composite extruded as nominally straight strands of about 2-mm diameter [4]. When loaded into an igniter tube, the channels between the strands permit easy flame penetration so that the Benite load should light more uniformly and quickly than a packed bed of granular material, all other things being equal.

The desired loading density (about 50% cross-sectional density) resulted in a snug but not tight loading of 18 g of near full-length Benite strands (lot RAD-SR11-75). A full-length foam liner was used in the paper cartridge. A 2-g priming charge in the 0.50-cal. case resulted in a 688-ms ignition delay, but very clean traces. Upping the priming charge to 4 g under the same loading

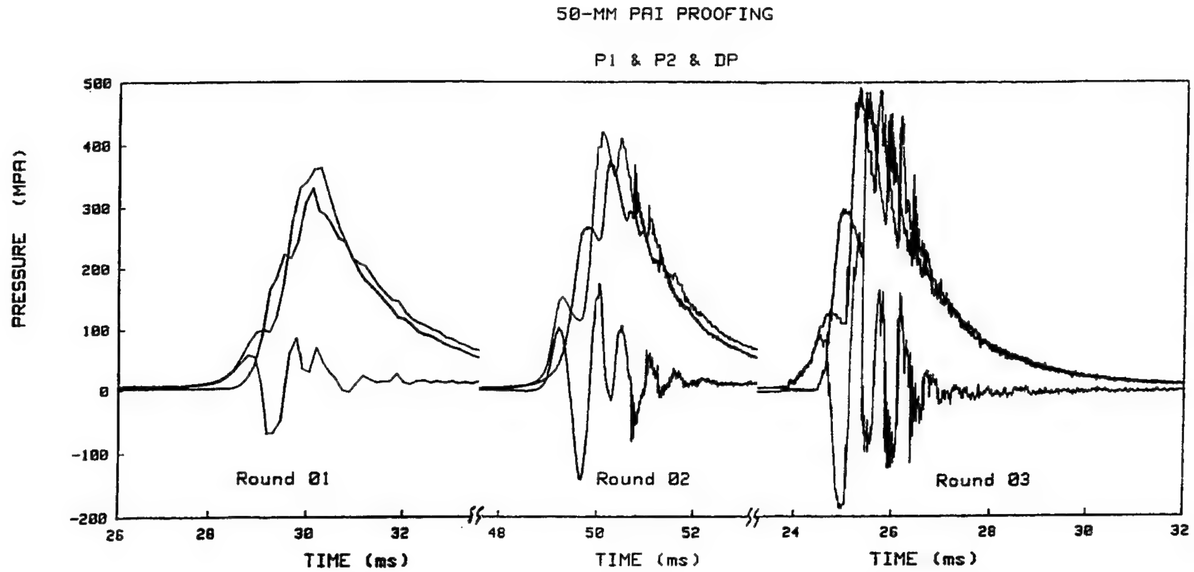

Figure 6. Effect of Priming CM. (Sampling rate was increased after shot TED01. 900-g in-bore mass, 750-g, 0.0125-inch web, 7P M30. Priming: TED01, 12 g; TED02, 8 g; TED03, 16 g, spit tube blown away, 0.50-cal. case stuck.)

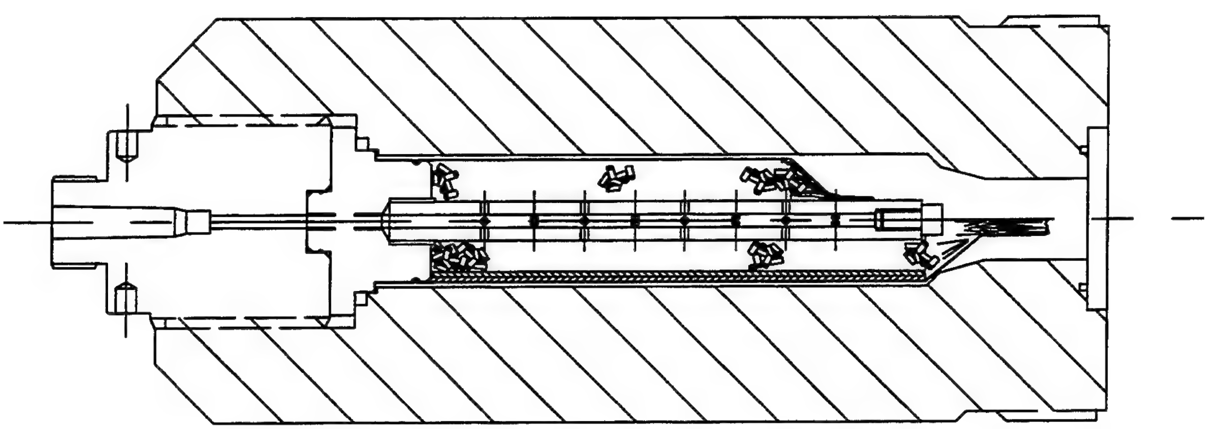

Figure 7. Effect of Foam Liner on Disposition of Ullage. (Free volume is reduced adjacent to the chamber wall [lower half of view] to the point where propellant covers the igniter tube.)

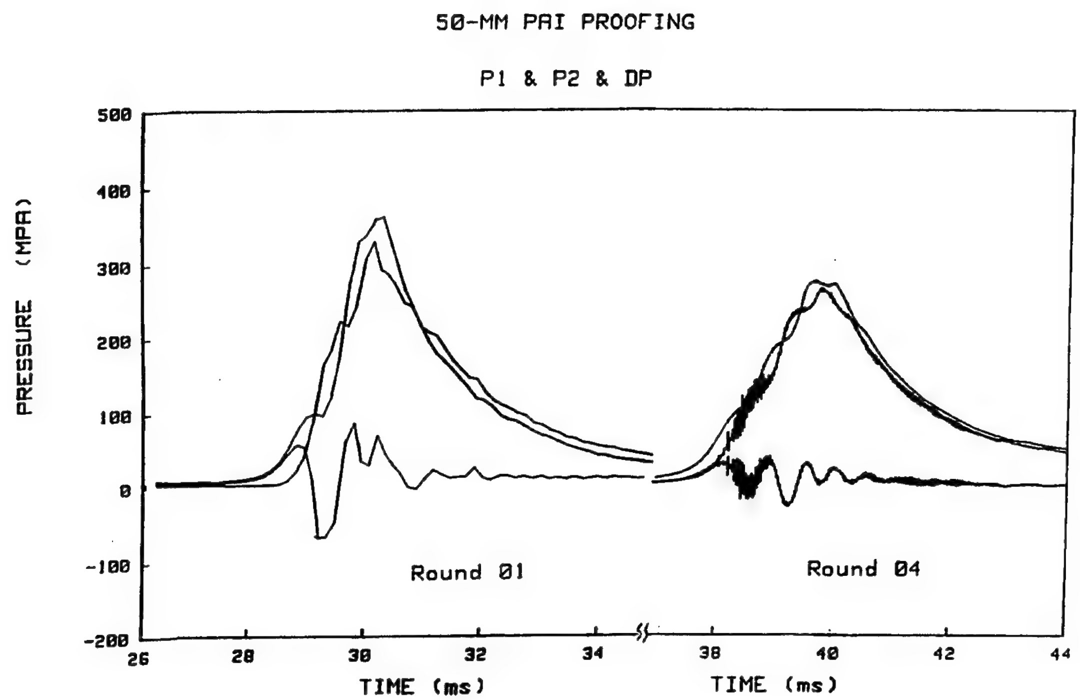

Figure 8. Effect of Foam Liner on P-T Traces. (No foam liner, TED01, compared with foam liner, TED04, under the same loading conditions: 900-g in-bore mass, 750-g 0.0125-inch web 7P M30 propelling CM, with a 12-g priming charge.)

conditions decreased the ignition delay to 160 ms, but oscillations were evidenced in the P-T traces, with a maximum negative pressure difference of −22 MPa. The consensus of opinion was that the spit hole diameter was too large compared with the cross section of the igniter tube cavity, so that much of the priming gases went out the first few holes, effectively base-igniting the charge.

A new igniter tube, designated Model 1, was made up, with an 11-inch-long (280 mm) pattern of pairs of 5/64-inch (2 mm) holes on 2-inch (51 mm) centers, alternating 90°. One additional pair of spit holes was accidentally drilled between the top two pairs of holes, and three spit holes were drilled into the plug at the tip of the igniter tube, inclined off axis forward. The sum of the areas of the spit holes was slightly less than the cross-sectional area of the central hole, to ensure an even distribution of the fire. Returning to the conditions of the fourth shot, 12 g of priming powder in the

0.50-cal. case vented into an empty igniter tube in a 750-g charge centralized on the igniter tube by use of a foam liner.

The gun went "pop," and the shot went downrange, accompanied by a small puff of smoke. The chamber pressure was just above the background noise level. Apparently, the main propelling charge had not lit. After a half-hour wait, the gun was examined. No unburnt propellant was noted at the muzzle. No unburnt propellant in the 0.50-cal. case was noted. The chamber was unloaded. There was a regular pattern of dark scorch marks on the kraft paper holding the charge corresponding to the spit hole pattern, and the paper cartridge had been popped open. Opening the paper and examining the main propelling charge revealed that the foam liner surrounding the charge was melted in about 25-mm-diameter spots at every spit hole location, and the propellant bed had lit and extinguished in a line out from each spit hole. The peak pressure measured about 5 MPa on both the rear and forward gauges. Evidently, the chamber failed to pressurize rapidly, and the powder extinguished with the sudden pressure drop on shot ejection.

For the next shot, the spit holes were drilled out to 1/8-inch diameter (3.2 mm), the number of spit holes at each station doubled to four, and the pattern density doubled, to yield a pattern of 48 holes, with the additional three in the plug at the tip. This variant was designated Model 2. The cross-sectional area of the spit holes was now four times that of the central hole, but still considerably less than that of the original PAI igniter tube or of our surrogate. Under the same loading conditions (12-g priming, no Benite in the spit), the gun fired promptly but displayed classic pressure waves, worse than those under the same conditions using our original 3/4 inch-diameter brass igniter tube with the larger holes.

Dr. Chang pointed out that when one observes ignition anomalies due to improper priming design, there is a lot of round-to-round variability in the performance, so that the two traces in Figure 9 may not be indicative of significantly different performance.

Having spent eight shots and gone full circle, Benite was indicated. We used the Model 2 igniter tube, loaded with 18 g of Benite and lit with 5 g of priming powder. Ignition was prompt, and the

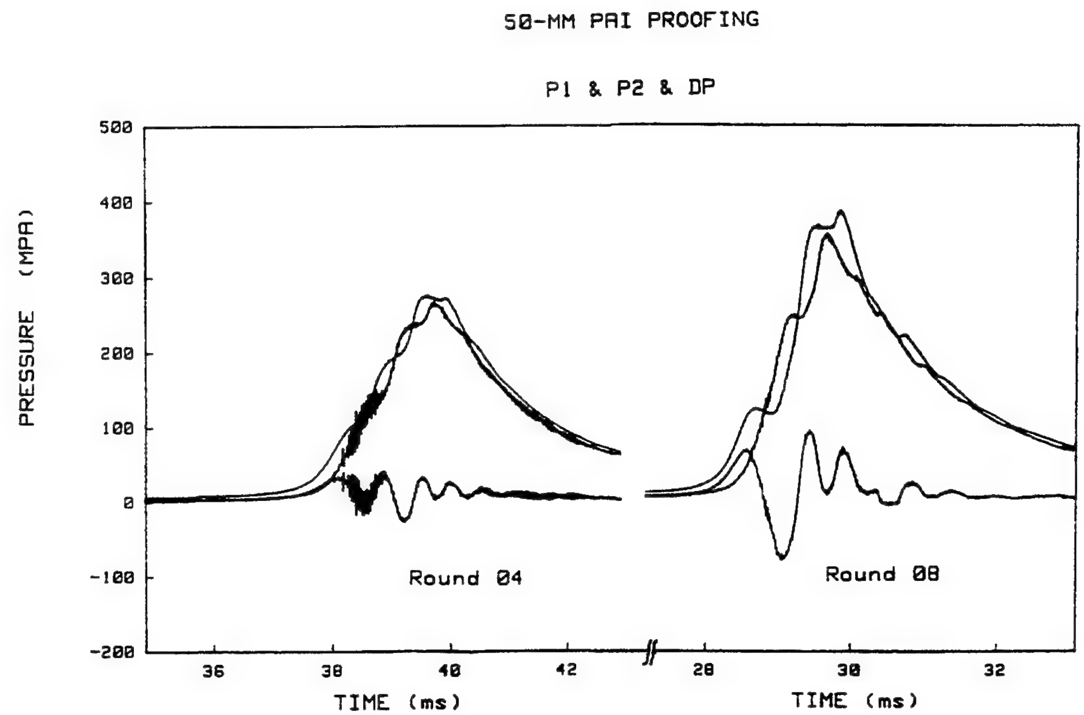

Figure 9. Performance of Empty Igniter Tubes With Differing Hole Patterns. (TED04: 32 holes, 3/16-inch diameter, 0.88 inch^2. TED08: 51 holes, 1/8-inch diameter, 0.62 inch^2. 900-g in-bore mass, 750-g, 0.0125-inch web, 7P M30 propelling charge centralized with foam, 12-g priming charge.)

pressure traces were clean. We then stuck with this design as we varied the pressure for the proofing process. Observe the improvement in pressure traces between shots TED08 (no Benite) and TED09 (Benite-filled spit tube, reduced priming propellant charge) in Figure 10.

At the end of the program, we examined the effect of putting Benite in the PAI-supplied igniter tube. At approximately 50% loading density, it took only 13 g of Benite. Firing the 900-g proof slug with 750 g of propellant, the P-T traces displayed slight pressure waves, with a maximum negative pressure difference of −27 MPa. This value is low enough that further refinements to the priming using that igniter tube could be done when the gun is placed in service, providing that the in-bore and propelling CMs provide fairly low pressures, and that the results of such experimentation be monitored closely.

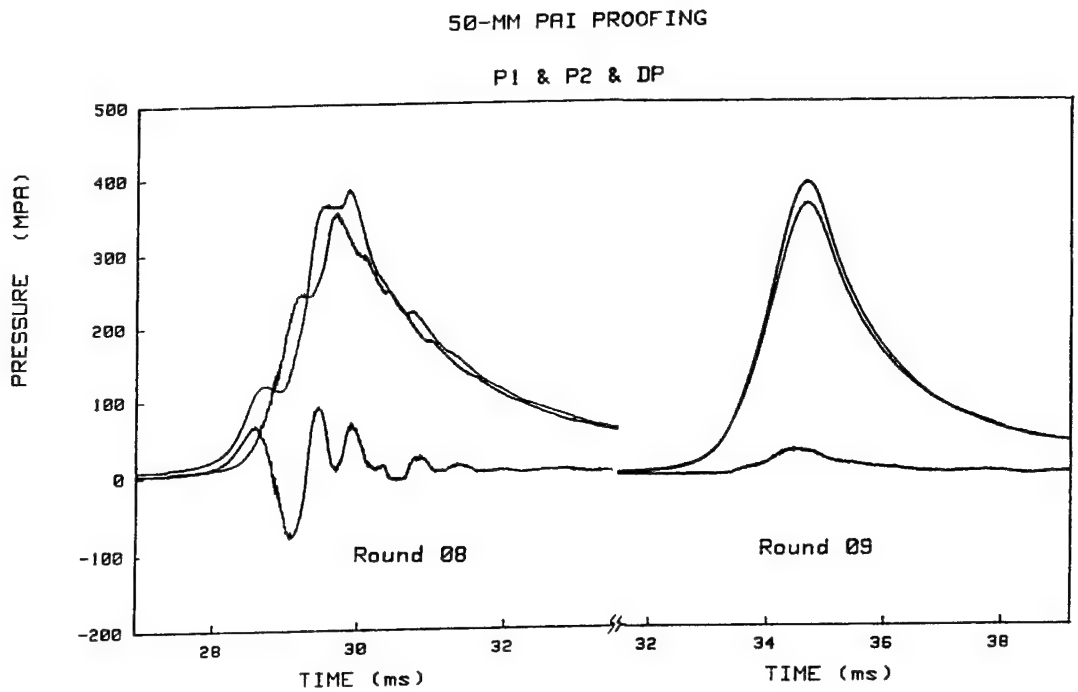

Figure 10. Effect of Benite Fill on Ignition. (TED09: 5-g priming charge, 18 g of Benite in the igniter tube. TED08: 12-g priming charge and an empty Model 2 spit tube. 900-g in-bore mass, 750-g, 0.0125-inch web, 7P M30 propelling charge centralized with foam.)

Figure 11 compares the best (TED09) and worst (TED14) pressure traces for the Benite-filled Model 2 igniter tube with the P-T trace resulting from a Benite-filled PAI igniter tube (TED15). TED09 and TED15 had the same 750-g main propelling charge, but different Benite loads in a different spit, with a nominal P_{max} of 660 MPa (96 ksi) while TED09 and TED14 are for the same priming but with a 1,050-g main propelling charge (P_{max} about 640 MPa [92 ksi]) on TED14.

4. Proof-Testing

4.1 Purpose. The previous discussions covered the ignition and pressurization issues of the interior ballistics. The main purpose of the effort was, however, proof-testing the gun. In proof-testing, the gun is intentionally subjected to a tensile stress state significantly higher than the maximum to be expected in service, even under the most unusual conditions. While this is primarily

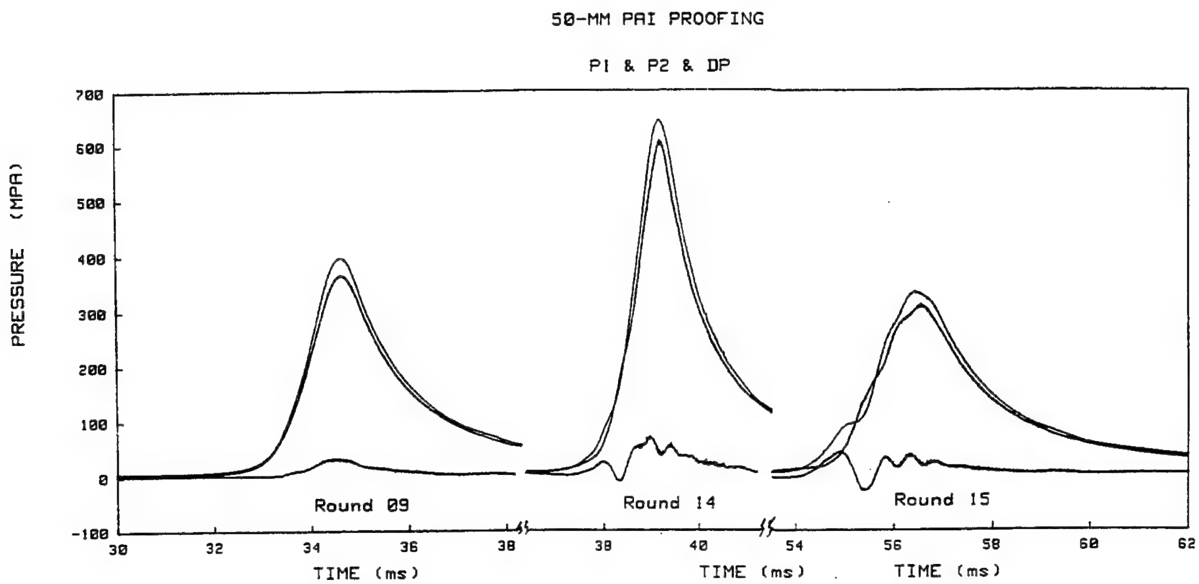

Figure 11. Performance of Benite-Filled Igniter Tubes Under Various Conditions. (900-g in-bore mass, 5-g priming charge, various propelling charge loadings of 0.0125-inch 7P M30. TED09: low-pressure shot, ARL igniter tube. TED14: high-pressure shot, ARL igniter tube. TED 15: low-pressure shot, PAI igniter tube.)

intended to detect gross flaws, the resultant partial yielding of the material induces favorable residual stresses that help to assure an adequate fatigue life under service conditions. (See texts on machine design for an exposition of fatigue and fracture mechanics [5, 6].)*

4.2 Fracture Mechanics Considerations. The process of fatigue failure has recently and more accurately been called progressive fracture. Fatigue failure becomes a consideration when ductile metal parts are subjected to cyclical stresses in which the peak tensile value exceeds some characteristic fraction of the yield stress. Cracks smaller than some critical size (which depends on the load) will then advance a small amount each cycle. If there are cracks larger than the critical crack size, either present initially or having grown in service, the part suddenly fractures. The

* Dawson [7] is an excellent open-literature publication on high-pressure containment.

crack size depends upon the stress applied, the shape and orientation of the crack, and the fracture toughness of the material. The fracture toughness, in turn, depends on the metallurgical state of the material. If a dimension of the part at the crack tip is thin relative to the length of the crack, plastic flow in the region around the crack tip will result in a ductile failure. When the part is thick relative to the critical crack size, the ultimate failure will be sudden and seemingly without warning.

In guns, the usual cracks that cause trouble are fatigue cracks that advance radially from the bore wall. If the wall is thin enough, these cracks can advance through the wall and vent gas before a crack can run catastrophically. This *leak-before-burst* condition provides a forceful visual indication that something is wrong, before a much more dangerous state is reached.

The higher the stress to which a part of a given fracture toughness is subjected, the smaller the critical crack size is. Survival of a part under the high stress of proofing assures that no flaws above this smaller critical size exist in the part. Then, in service, a large number of cycles of the lower values of peak tensile stress can be tolerated before any existing cracks grow to a (larger) size that is critical at the worst expected load in service. A program of periodic nondestructive examination is used to detect cracks well before they grow to such a size, so that the part may be condemned and destroyed before its use becomes dangerous.

4.3 Service and Proof Pressures. Service and proof pressures were established based on experience with our current 50-mm high-pressure powder gun, which is of a very similar geometry to the new PAI rear end. We cannot successfully launch any realistic projectiles at pressures exceeding about 550 MPa (80 ksi), which is taken to be the upper limit of useful service pressure. Because early in the current gun's history it had been inadvertently subjected to a chamber pressure of 900 MPa (130 ksi), this was set as the upper limit on the proof-test pressure.

The PAI chamber's ID is 3 1/4 inches (82.5 mm) and OD is 10 inches (254 mm). The barrel sections have a nominal 50-mm bore by a 7-inch (178 mm) OD. All are made of American Iron and Steel Institute (AISI) 4340 steel [7] with a strength of 1,100 MPa (160 ksi), based on the composition and the tempering temperature stated by the supplier's heat-treater. Using the von Mises

yield criterion, solving the Lame′ equations for an open-ended, thick-walled cylinder under the assumption of elastic-perfectly plastic behavior of the steel, the bore wall of the chamber and of the barrel will yield at essentially the same internal pressure of about 575 MPa (80–85 kspi) [8]. The burst pressures, using a simple empirical relationship that closely approximates [9] Southerland's integral solution [10] to the Weigle equation for radial stress in the plastic region [11], are 1,340 MPa (194 ksi) and 1,510 MPa (219 ksi) for chamber and barrel, respectively.

This predicted behavior is consistent with our experience with the current UDRI system. Early on, it was subjected to a number of shots exceeding 600-MPa breech pressure, a few to a maximum of 900 MPa (130 ksi). The gun continued in service. Several years later, when the chamber rear-seal surface was reconditioned in our machine shop, it was discovered that the chamber bore wall was locally distorted outward about 0.2 mm around the rear gauge port. The UDRI chamber now has about 1,000 shots on it.

4.4 Expected Service Life. Mr. Fararra's analysis [12] indicated that the barrel would fail in a ductile fashion. The chamber, with its thicker wall, would fail in a brittle fashion. If the parts were unflawed initially and show no flaws on inspection after the proofing, the autofrettage attending the proofing will result in a fatigue life so greatly exceeding the wear life (considering rebores, a wear life of approximately 1,000 cycles) that theoretically there is no need for further nondestructive examination of the parts. In practice, the parts will be inspected about every 300 shots. Periodic nondestructive examination of the UDRI gun's original chamber, of similar construction, has shown no reportable indications of cracks in either part.

4.5 Mechanical Response of Gun to Proofing. The chamber OD was measured in two planes located just forward of the center of the chamber from the two pressure taps. The mount permitted only one diametral measurement to be made at each point. The actual spots to be measured were circled with a marker, the measurement taken three times with a micrometer, and the diameters averaged. The nominal diameter of the chamber here is 10 inches (254 mm) (ID is 3.25 inches [82.5 mm]), and the actual diameters varied by about 0.15 mm (0.006 inch) between stations. A slight but not significant (well within the scatter of the individual measurements) permanent enlargement was noted between shots TED10 and TED11 (pressures 422 and 570 MPa [62 and

83 ksi]). Yield was predicted at 585 MPa (85 ksi). The OD increased by another 0.025 mm (0.001 inch) after the next shot at 763 MPa (111 ksi). The pressure vs. CM curve (discussed later) was rising considerably faster than the predictions, so that the increment in powder mass was set conservatively and resulted in a peak breech pressure of 828 MPa (120 ksi), which was an acceptable proofing pressure on shot TED13. The total enlargement of the OD after this shot from the unyielded dimension was 0.06 mm (0.00225 inch) and no further enlargement was noted on the following shots at 628 and 325 MPa (91 and 47 ksi), respectively.

The gas-bleed holes were covered by masking tape as a telltale, and no sign of leakage was ever detected, a tribute to the seal design. The only mechanical problem encountered was sticking of the priming cartridge case, which first occurred after the 760-MPa (110 ksi) shot. The breech plug was taken to the machine shop, and the case head was drilled and tapped 1/2-inch-13 Unified National Coarse (UNC) to accept a threaded spud on a slap hammer, and the case easily pulled out. The case stuck again on the 828-MPa high-pressure proof-shot but was again easily extracted as before. The subsequent 620-MPa (90 ksi) shot (the maximum pressure we would permit in normal operation) did not result in the case sticking.

The result of this proofing was modeled analytically under the assumptions stated earlier. When subjected to 830 MPa (120 ksi) under closed-end conditions, the chamber wall should be in a fully plastic state (yielded) out to a radius, c, of 1.265 times the inside radius, a (the outside radius is b). The stress distribution is displayed in Figure 12.

This figure plots stress on a vertical scale vs. position relative to the bore wall on the horizontal scale, underlaid by a broken-out section of the barrel as a visualization aid. Tensile stress is positive, while compressive stress is negative. The stress is plotted beginning at the bore wall, $r/a = 1$, and ending at the chamber OD, at an r/a value just over 3. The generalized state of stress due to the internal pressure, a tensor field, can be resolved into three principal components of stress, which lie along mutually perpendicular axes at an orientation at which shear stresses vanish.

For a thick-walled pressure vessel subjected to internal and external pressure only, the principal directions coincide with the radial, tangential, and axial directions. The stress in the axial direction

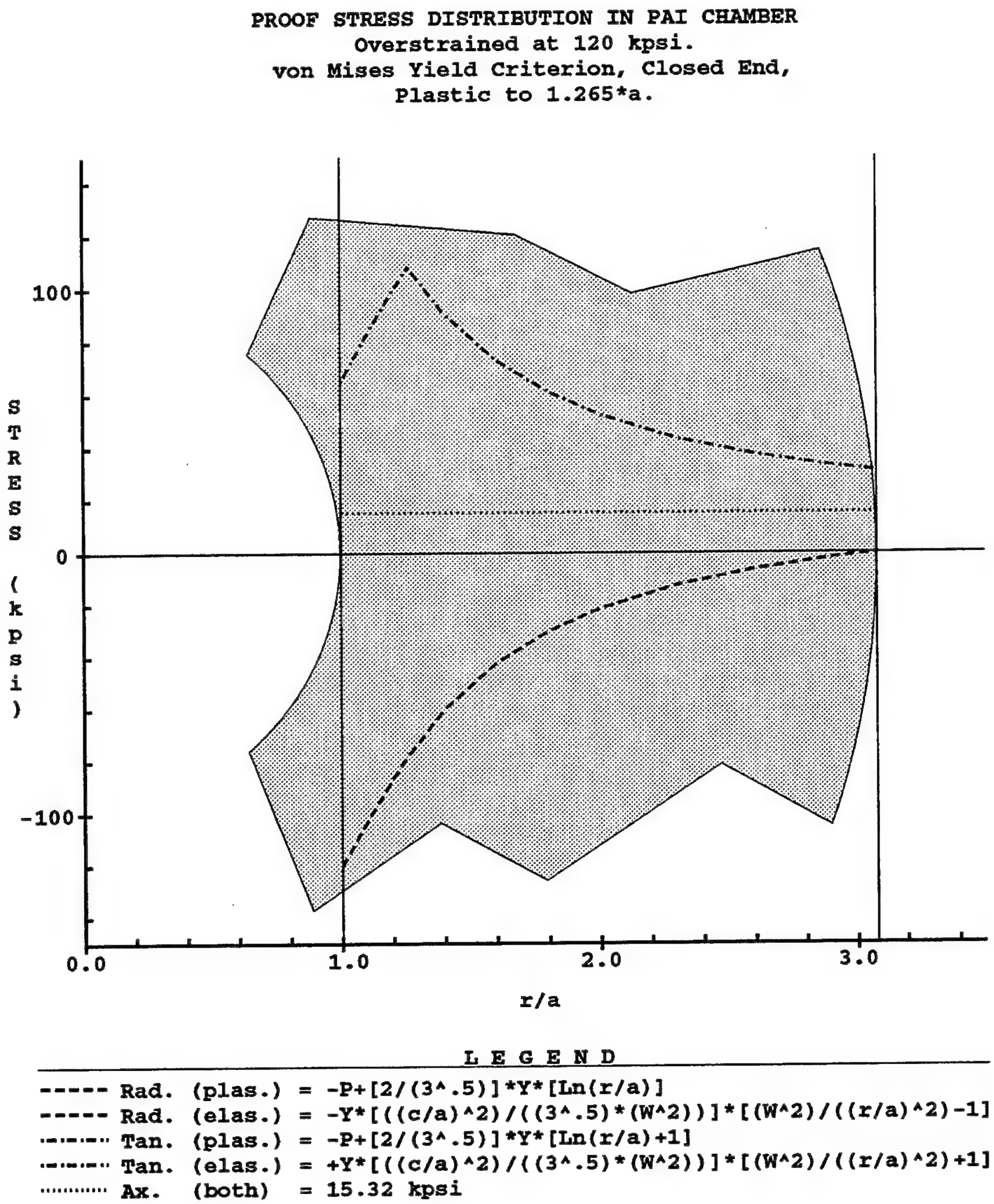

Figure 12. Stress Distribution in Chamber Wall During 830-MPa (120 ksi) Proof-Pressure Overloading. (Material is plastic from the bore wall to 1.265 times the bore wall radius.)

is assumed to be uniform and is a (relatively) low value in tension. The stress through the wall, in the radial direction, is constrained to be that of the internal pressure at the bore wall and drops smoothly in compression to a value of zero (or rather, atmospheric pressure) at the outer surface. Overpressure above that at which the bore initially yields results in yielding out to a certain point, $r = c$, and the hoop (tangential) stress rises to a peak in tension at this radius and then falls away with increasing radius.

When the load is released on a part that has partially yielded, a residual stress state results that will favorably resist a similar loading state up to the yield load. For thick-walled pressure vessels in which operating pressures stay well below the initial overpressure used to plastically deform them, this locked-in stress opposes the stress arising from the applied pressure, lowering the effective stress. Such autofrettaged vessels will behave elastically up to the autofrettage overpressure, even though the internal pressure exceeds that which would have caused the part to yield initially. The residual stress state and the resultant working stress in the PAI chamber under maximum working pressure (90 ksi) are shown in Figure 13. Having a similar wall ratio, the barrel will respond similarly.

5. Interior Ballistics

5.1 Velocity vs. CM. The velocity data were problematic at best. Down-bore Doppler radar velocities were captured on only the first four shots. Increasingly bad pressure waves on the first three shots could be invoked to explain the decreasing velocities, but the pressure waves on the fourth shot were only marginal, and yet the velocity was the lowest of the four. Blow-by prevented determining the velocity of the rest of the shots. Weibull radar looking downrange was then added, but the records were ambiguous, so that the Weibull velocity reported is thus a judgment call. On the first Weibull record, shot TED11, the projectile could have had one of two velocities. On the other three records, velocity was a bit more certain.

To see how well the velocity data matched the IBHVG2 predictions, a power law form was fit to the IBHVG2 predictions and to the data. The data were assigned weights based on their credibility

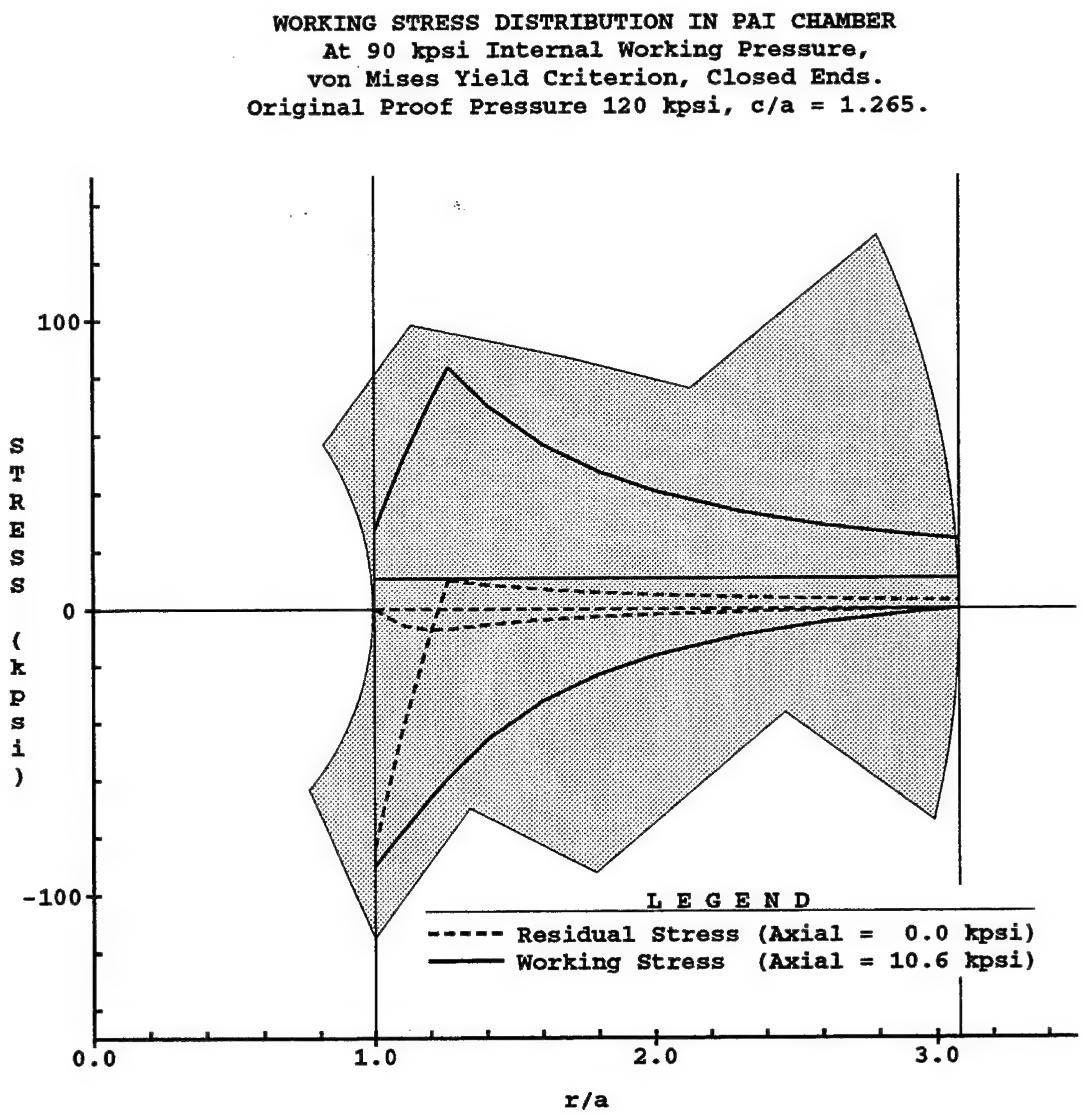

Figure 13. Residual and Maximum Working Stress Distributions in Chamber Wall. (For 620-MPa [90 ksi] chamber pressure after 830 MPa [120 ksi] proof-load.)

as follows: the first two velocity points were given a weight of four, the next two one, and each of the two values from the first Weibull record one apiece. The other three Weibull points were given weights of two. The fit to the IBHVG2 predictions lies within the scatter band around the fit to the data, lending credibility to the model used to make the predictions. However, the scatter in the data is so bad that these data will probably not be useful in preparing powder-loading curves (see Figure 14).

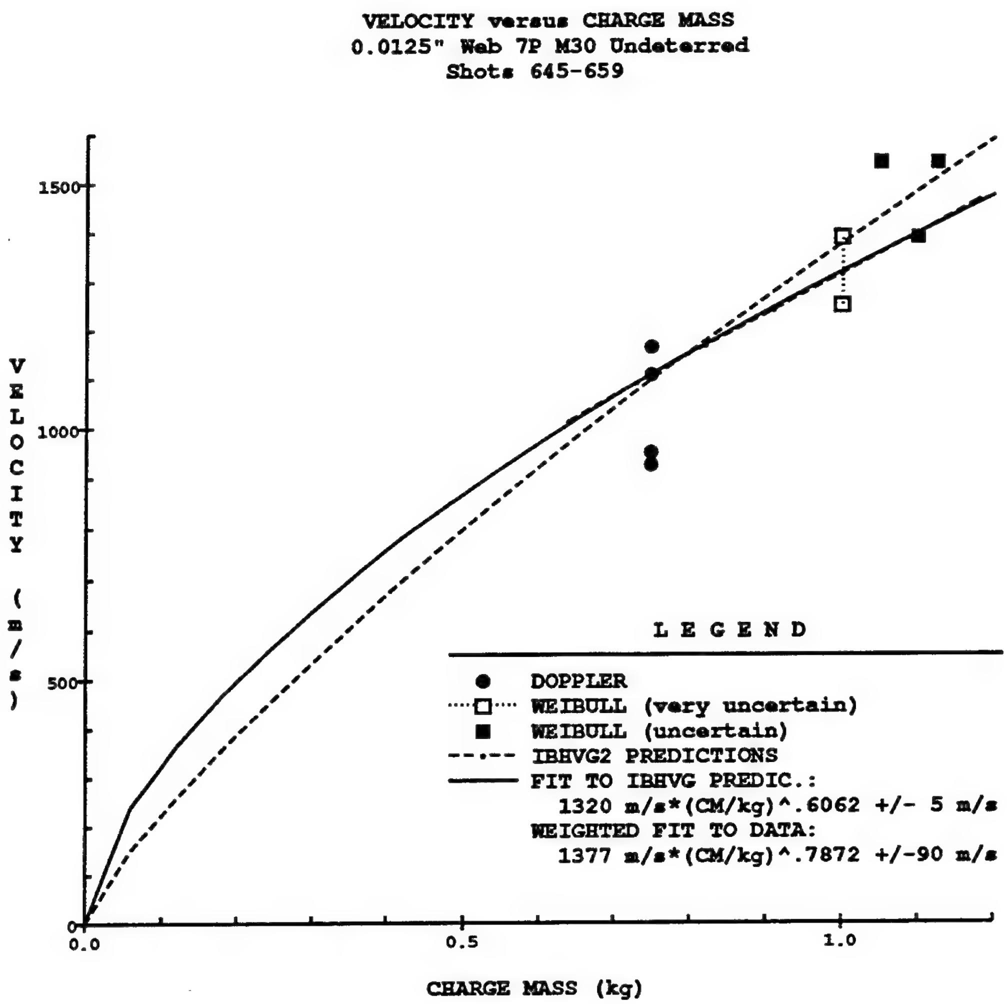

Figure 14. Velocity vs. Propelling CM for PAI Chamber on the 50-mm Gun.

The piezoelectric pressure gauge output was captured and corrected by the individual gauge-calibration factors. The breech face and forward chamber pressures were subtracted, and two P-T traces and their difference traces were plotted. Judgment was used to categorize the pressure traces as being the result of bad, marginal, or good ignition, and the peak breech face pressures were then plotted as a function of CM (see Figure 15). The data are also tabulated in the Appendix. The effect of the bad ignition is obvious in the scatter in the data at the 750-g loading. The point just above zero pressure on the plot is from the shot in which the charge was probably extinguished on shot ejection. Peak breech pressure on that shot was approximately 35 MPa (5 ksi).

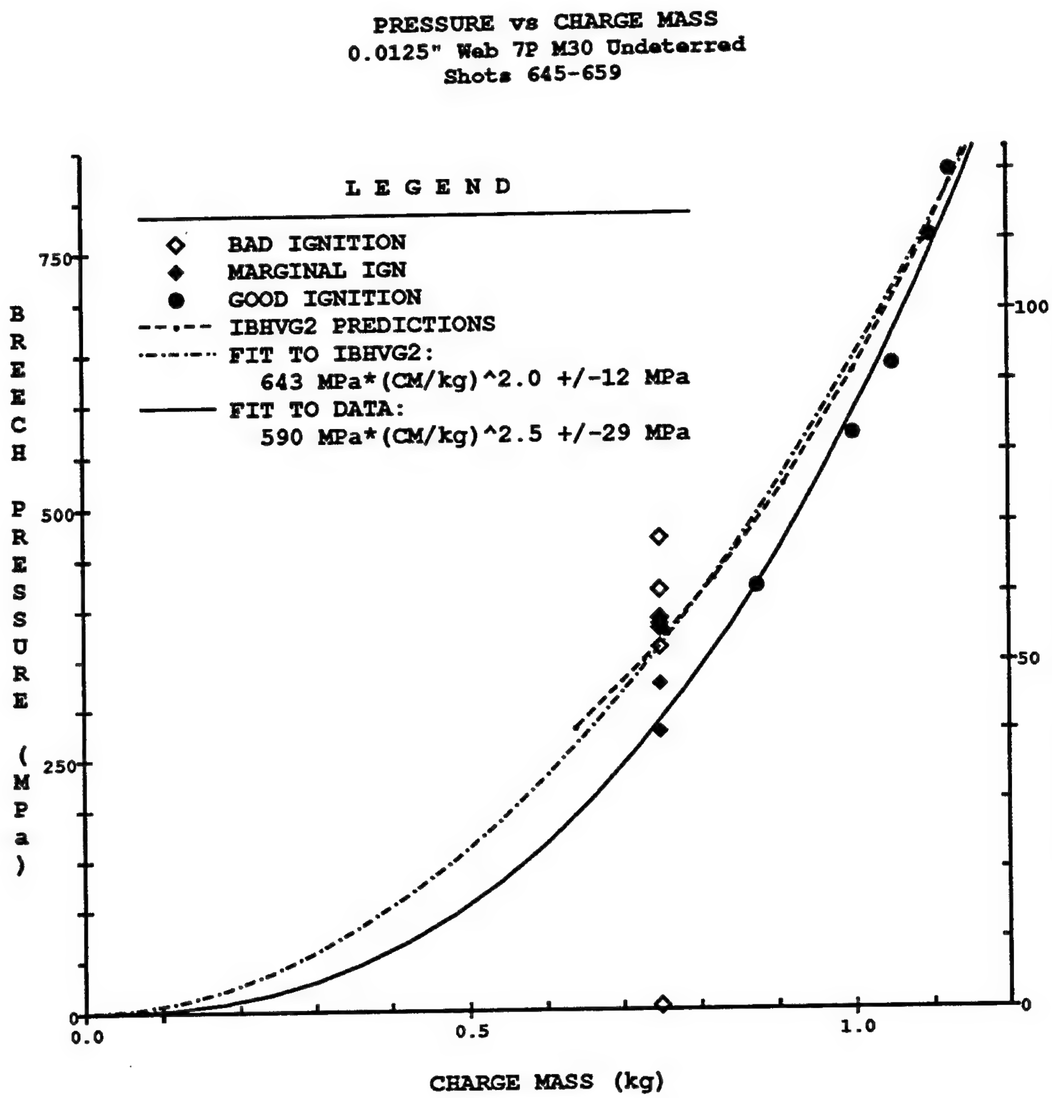

Figure 15. Pressure vs. Propelling CM for PAI Chamber on the 50-mm Gun.

The pressure vs. CM data for the UDRI gun in Range 309A is fit reasonably well with a simple upwardly directed parabola, as was the IBHVG2 prediction for the PAI chamber. However, such a fit was not satisfactory for the actual set of performance data (dashed curve). Allowing the exponent to vary from its value of 2 in the originally parabolic form gave a very reasonable fit with only two parameters (solid line).

5.2 Mechanical Response of Priming Cartridge Case to High Pressures. Figure 16 photographically shows the smooth progression of mechanical deformation of the 0.50-cal. case heads with increasing pressure. This response permits the use of observed deformation to generate a rule-of-thumb estimate of pressure. First, the percussion cap becomes increasingly flattened (top row), and then the metal raised in stamping the identification into the case head becomes increasingly flattened, particularly evident in the character "6." Radial flow of the case into the extractor grooves begins to be evident at about 570 MPa (upper right) and is extreme in the 763- and 828-MPa instances (lower middle and right, respectively). Similarly, the primer pocket first begins to grow radially; then gross radial plastic flow of the case head is observed. The irregularities seen on the end of the lug of metal extruded into the extractor groove results from prying (or attempting to pry) the case from the chamber. Observation of such trends has long formed the basis for the handloader's rules of thumb about pressure in the case. Having measured chamber pressure, this relationship can be calibrated, and is done so in Table 1.

The 0.50-cal. case communicates with the chamber through a restrictive hole so that some care needs to be exercised in drawing conclusions from this crude visual means of estimating case internal pressure. For example, 16 g of IMR 3031 was loaded into the 0.50-cal. case on the third shot, and the case stuck. The head stamping on the case was flattened to about 50% of normal depth. Based on the similarity of deformations observed, one could assume that the large charge of rifle powder in the case caused about the same case pressure as the shot with the breech-face pressure of 763 MPa (about 110 ksi), in which there was only 5 g of rifle powder in the 0.50-cal. case, but a much larger main propelling CM. Thus, a 0.50-cal.-cartridge case sticking when the chamber pressure is below 550 MPa (80 ksi) is an indication of too great a priming CM irrespective of the presence or absence of irregularities in the pressure traces. Most importantly, any sticking of a case in this system would be cause to believe that the gun is being operated above an acceptable pressure, though it could be that only the priming case was being overloaded.

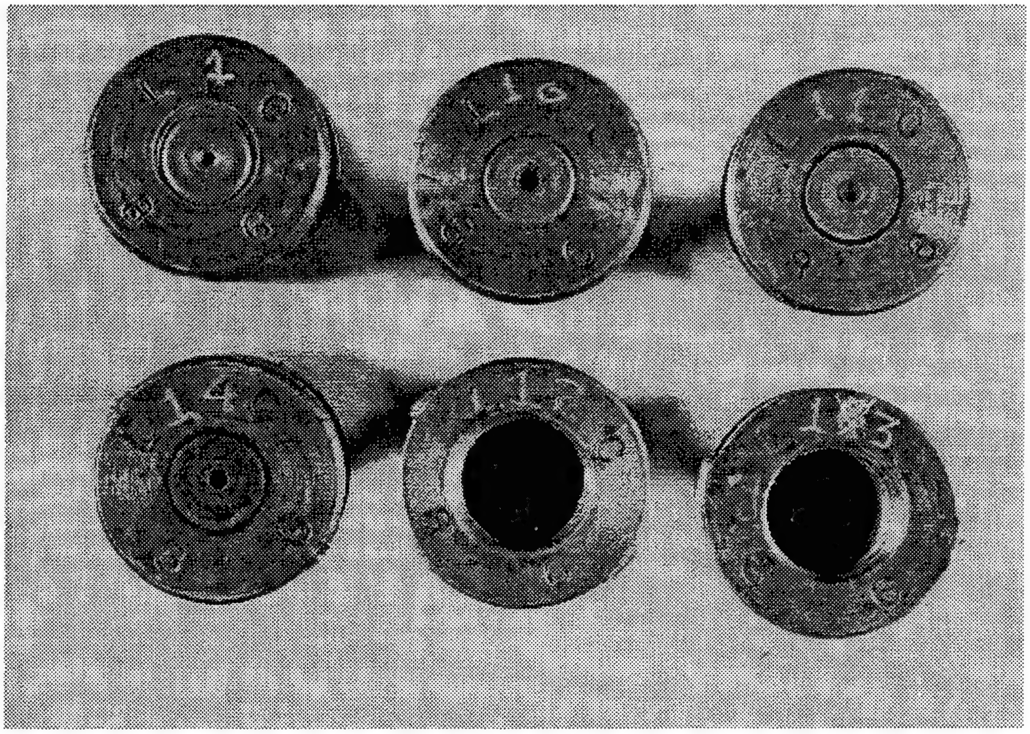

Figure 16. Case Head Deformation With Increasing Pressure. (Breech-piezo gauge pressures of 362, 422, and 570 MPa [left to right, top] and 633, 763, and 828 MPa [left to right, bottom]. Note increased flattening of percussion cap and head stamping, and lugs extruded into the extractor grooves, first visible on the case in the shot at 570 MPa [upper right]. The percussion cap is slightly loose in the expanded pocket at 633 MPa.)

Table 1. Observed Response to Pressure of 0.50-cal. Brass Case in PAI Cap Breech

Pressure (ksi)	Observed Response			
	Raised Metal or Depth of Stamping	Percussion Cap	Machining on Head	Radial Flow Into Extractor Pockets
50	No change	No change	No change	None
60	Completely flattened	No change	No change	None
80	Completely flattened	Flattened	Mostly flat	Slight
90	Stamping shallow	Flattened	Mostly flat	Slight
110	Stamping shallow	Flattened	Mostly flat	Significant, case stuck
120	Figures widen	Fall out	Mostly flat	Considerable, case stuck

6. Conclusions

The PAI breech end hardware is ready to be placed in service. The chamber, charge holding plate, plug breech, cap breech, and associated hardware survived the proof-testing to 828 MPa with no significant problems.

Yielding of the chamber wall was observed at the expected pressure, and some permanent deformation induced at higher pressures, so that the gun has been autofrettaged in the process of the proof-test. In addition to boosting peak service pressure, autofrettage assures that the system will withstand subsequent overloading without further permanent deformation, as well as extending the expected fatigue life significantly. Nonetheless, the chamber, plug breech, and cap breech should be nondestructively examined for cracks periodically (approximately every 300 shots or so) and be destroyed if any significant cracks are discovered.

Gun users are advised, however, against the practice of using the pressure of firing to autofrettage guns because of the tremendous amount of energy stored in the hot, highly compressed propellant gases. In the event of a failure, a gun explosion is incredibly destructive. Service weapons and other pressure vessels of favorable geometry are currently autofrettaged by mechanical overstrain achieved by swaging with a series of mandrels or, alternatively, by hydrostatic overstrain, in which the pressure is achieved hydraulically, with essentially all of the free volume taken up with metal displacers to minimize stored energy.

The interior ballistic data in this program were developed using a well-characterized propellant, which in turn permits refining IBHVG2 predictions to pressures well above those that should ever be experienced in service, both in this gun and in other similar high-pressure gun systems. The unexpected problems with the priming forced us to resolve them, in the process obtaining valuable information that will permit the users to minimize future priming problems and hence obtain the best performance from the system. The procedure developed for removing stuck priming cases is simple to implement and, hence, is recommended. The photographic and descriptive record connecting

measured pressure and case head deformation should be generally useful to gunners using brass cartridge cases in situations where directly gauging pressure is difficult or impossible.

A number of lessons were learned in the proof-testing program. The 50-mm bore ID was large enough to permit field measurement of in-bore acceleration by Doppler radar, but increasing blow-by after a few shots caused loss of signal. The small radar cross section of the proof slug made velocity measurement by Weibull radar problematic. This was made worse by the loss of the plastic carrier in flight that loosed the main metal slug and smaller ballast slugs. The CC gauges yielded measurements above 690 MPa (100 ksi), but these measurements were low. The piezo gauges had to be removed from their ports and the ports cleaned and refilled with grease after each shot because paper from the cartridge would sometimes be forced into the port holes.

Some initial operational recommendations arose from this experience. The priming case will withstand any overload to full-up with IM 3031 as priming propellant, but this will result in bad ignition. The priming case will stick in its chamber at main chamber pressures of about 620 MPa (90 ksi), but this pressure is higher than expected in normal service. The cases can probably be rodded out, though we drilled and tapped the head to 1/2-inch-13 UNC and extracted them with a slap hammer. A foam liner should be used to bring the main propelling charge about 20–30 mm over the tip of the igniter tube. Ignition is exquisitely sensitive to ignition train design. Pressure waves rob some velocity and at the same time reduce the maximum charge that can be loaded to keep predicted peak pressure perhaps 100 MPa below the service limit due to added erratic pressure fluctuations. Benite is needed to avoid pressure waves. A near-ideal priming recipe for our small-web M30 propellant is 5 g of IMR 3031 in the 0.50-cal. case spitting into the igniter tube loaded with full-length strands of Benite to a snug, but not tight, fit, taking up approximately 50% of the cross-sectional area. In the Model 2 igniter tube, this Benite loading is 18 g, while the PAI igniter tube took 13 g.

The only problem we had was with the firing pin, which is an assembly and should be monolithic. We machined the tip from its original configuration to a smaller radius, but as modified it sinks too deeply into the primer and perforates it frequently. The high-pressure seals worked well, and experience indicates that the O-ring in the breech should be changed every 10 shots or so. We have

had better performance out of O-rings made of polytetrafluoroethylene with a silicone rubber core. The very short gun recoiled in its mount about 1.0 to 1.4 inches depending on loading, with the whole assembly sliding rearward 12–18 inches. This suggests that the recoil system will be quite adequate when the PAI breech end is assembled to the full 6 m of barrel.

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Appendix:

Data Tabulation

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Interior Ballistics - Proof-Testing PAI Breech End
Range 309A Dummy Shot Numbers 645–659 at Range 18
0.0125-inch Web 7P M30 Lots RAD-771-4 and RAD-E-29

Line No.	R309A Shot No.	R18 Shot No.	Tape 472 Ident	IMR-3031 Chg. Mass (g)	Ign. Tube Model	1 Wrap Foam W. (inches)	Benite in Spit (g)	Audible. Ign. Delay	Meas. Delay (ms)	T1 (ms)	T2[a] (ms)	Chg. Lot RAD-
1	645	TED01	44	12	81006-2	0	0	Prompt		28.1	32.4	771-4
2	646	TED02	45	8	81006-2	0	0	Prompt		48.7	53.5	771-4
3	647	TED03	46	16	81006-2	0	0	Prompt		23.8	27.1	771-4
4	648	TED04	47	12	81006-2	12	0	Prompt		37.3	41.9	771-4
5	649	TED05	48	2	81006-2	12	18	3/4 s	688			771-4
6	650	TED06	49	4	81006-2	12	18	Not aud.	160	80.6	86.0	771-4
7	651	TED07	50	8	Model 1	12	0	Pop!	NR[b]	27.5	NR	771-4
8	652	TED08	51	12	Model 2	12	0	Prompt		27.8	32.0	771-4
9	653	TED09	52	5	Model 2	12	18	Prompt		33.0	37.0	771-4
10	654	TED10	53	5	Model 2	12	18	Prompt		47.8	52.0	E-29
11	655	TED11	54	5	Model 2	8	18	Prompt		41.4	NR	E-29
12	656	TED12	55	5	Model 2	4	18	Prompt		39.2	43.7	E-29
13	657	TED13	56	5	Model 2	5	18	Prompt				E-29
14	658	TED14	57	5	Model 2	6	18	Prompt		37.4	42.0	E-29
15	659	TED15	58	5	PAI-175-013	12	13	Prompt		54.1	NR	E-29

[a] Shots TED06–15: T2 is approximate. Blow-by obscures Doppler radar signal from which shot exit is determined.
[b] No record.

Interior Ballistics - Proof-Testing PAI Breech End
Range 309A Dummy Shot Numbers 645–659 at Range 18
0.0125-inch Web 7P M30 Lots RAD-771-4 and RAD-E-29 (continued)

Line No.	R309A Shot No.	C. M. (g)	In-bore Mass (g)	Shot Base Fwd. R.F.T. (mm)	Package Fit	Muz. Vel. (m/s)	M. V. Credible?	Max. of 2 CC (MPa)	Piezo-1 Trace Shape[c]	Piezo-1 Pressure (MPa)
1	645	750	901	0	Light hand	1109	Y	344	PPPP	362
2	646	750	900	−10	Lodged	1166	Y	394	PPPP	419
3	647	750	901	0	No resistance	952	Y	534	2 Bad 2 Call	470
4	648	750	902	0	Light jacking	928	Y	Not used	IIP	277
5	649	750	901	0	Moderate jacking	NR	N	Not used	I	385
6	650	750	899	0	Moderate jacking	NR	N	Not used	SII	391
7	651	750	896	0	Moderate jacking	NR	N	Not read	Primer only	5
8	652	750	900	0	Moderate jacking	NR	N	357	PPPP	381
9	653	750	896	0	Moderate jacking	NR	N	370	C	390
10	654	875	899	0	Moderate jacking	NR	N	392	C	422
11	655	1,000	902	0	Moderate jacking	1252/1390	Barely	534	C	570
12	656	1,100	893	−20	Lodged	1391	Barely	687	C	763
13	657	1,125	903	−25	Lodged	1543	Barely	725	I	
14	658	1,050	903	0	Moderate jacking	1544	Barely	599	Sight I	638
15	659	750	903	0	Moderate jacking	NR	N	Not used	NII	325

[c] Nonparametric coding indicating quality degradation of P-T trace. Number of characters indicates number of undesirable features.
C = Clean rise and fall.
I = Inflection in slope.
N = Nearly forms a distinct peaked short-duration feature.
P = Peaked (rounded crest) short-duration feature.
S = Spike (sharp peak).

Interior Ballistics - Proof-Testing PAI Breech End
Range 309A Dummy Shot Numbers 645–659 at Range 18
0.0125-inch Web 7P M30 Lots RAD-771-4 and RAD-E-29 (continued)

Line No.	R309A Shot No.	Piezo-2 Pressure (MPa)	Piezo-3 Pressure (MPa)	Piezo-4 Pressure (MPa)	Max. Neg. Delta P. (MPa)	Pressure Wave Comments.	$P1_{max}$ Time (ms)	$P2_{max}$ Time (ms)	$P3_{max}$ Time (ms)	$P4_{max}$ Time (ms)
1	645	317	256	119	-69	P-T: Narrow steps				
2	646	372	262	94	-138	Classic Press. waves				
3	647	453	197	91	-186	Terrible				
4	648	267	201	129	-3/-26	Slight				
5	649	365	233	107	-5	No				
6	650	329	250	114	-22	Slight				
7	651	5	Noise	Noise	NR	N/A				
8	652	353	306	112	-75	Classic				
9	653	360	257	116	0	No				
10	654	383	268	129	-14	Slight P2 > P1	50.28	50.22	50.25	51.39
11	655	529	367	150	0	No	43.60	43.60	43.80	44.70
12	656	683	367	140	0	No	41.20	41.20	41.50	42.30
13	657					Slight				
14	658	602	378	159	-11	Very Slight	39.20	39.30	39.50	40.30
15	659	302	233	116	-27	Slight	6.52	56.65	56.71	57.76

Interior Ballistics - Proof-Testing PAI Breech End
Range 309A Dummy Shot Numbers 645–659 at Range 18
0.0125-inch Web 7P M30 Lots RAD-771-4 and RAD-E-29 (concluded)

Line No.	R309A Shot No.	General Comments
1	645	
2	646	
3	647	Halt and try foam in chamber to centralize charge.
4	648	
5	649	Only slight glitch on trace.
6	650	Noisy traces.
7	651	Shot TED07: Spit tube Model 1 is 7/16-inch ID by 3/4-inch OD with a uniformly distributed pattern of 12 pairs of two 5/64-inch-diameter spit holes, plus two extra (mistake), plus three at tip. It is used with adapter 91021 to give a 14-inch-overall length. The adapter has a 5/16-inch diameter by 1/2-inch-long hole at the base to admit primer gases. No paper liner in spit tube. Shot TED07: Main charge lit at spit jets, extinguished on shot ejection. Foam melted about 1-inch diameter but kraft paper only scorched. Output insufficient to light main charge rapidly enough.
8	652	Shot TED08: Spit tube model 2 is model 1 with a new hole pattern, 12 sets of four 1/8-inch-diameter spit holes, plus three at the tip. No paper liner in spit tube. Shot TED08: Pressure waves indicate holes too large, base-ignited charge.
9	653	Shots TED09–15: two wraps of Visicorder paper lined the spit tube.
10	654	Begin proof-test.
11	655	
12	656	Priming case stuck.
13	657	Priming case stuck.
14	658	
15	659	PAI spit w/Benite. PAI spit is 5/16-inch ID by 0.96-inch OD by 13 1/2-inches long with eight pairs of 3/16-inch spit holes. Snug Benite load was 13 g, with two wraps Visicorder paper as liner. After the shot, paper was wadded up, plugging the tip of the spit tube.

List of Abbreviations

AISI	-	American Iron and Steel Institute (a promulgator of consensus standards for materials)
ARL	-	U.S. Army Research Laboratory
ATC	-	Aberdeen Test Center
cal.	-	caliber
CC	-	copper crusher
CM	-	charge mass
ID	-	inside diameter
IMR	-	Improved Military Rifle (a former Dupont trademark)
NDE	-	nondestructive examination
OD	-	outside diameter
P-T	-	pressure-time
PAI	-	Physics Applications Inc., Dayton, OH
PFD	-	Propulsion and Flight Division, ARL
TED	-	Terminal Effects Division, ARL
UDRI	-	University of Dayton Research Institute
UNC	-	Unified National Coarse (60° vee-form thread descriptor)

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13. ABSTRACT *(Maximum 200 words)*

Reported here is the effort to proof-test a newly acquired breech-end assembly for the 50-mm high-pressure powder gun for terminal ballistic testing in the U.S. Army Research Laboratory's (ARL) Range 309A (R309A). The performance of a custom-produced 0.012-inch web 7-perforation M30 propellant in routine use there was modeled by the ARL-developed one-dimensional (1-D) interior ballistic code IBHVG2 to select a propelling charge mass (CM) that would produce a pressure of approximately 130 ksi for the purpose of proof-testing the gun. Proof slugs of the appropriate mass, 900 g, were fabricated. The breech end was assembled to a scrap 0.6-m piece of barrel to add mass, mounted in a hastily built fixture, and fired without recoil system at ARL's barricaded Range 18. The priming system and recipe supplied with the Physics Applications Inc. (PAI) breech end was adjusted until a pressure-time (P-T) curve with acceptably low-peak negative differential pressures was obtained. This required reducing the propellant in the 0.50-cal. case used as a primer and putting Benite strands in the spit tube.

Following establishment of a suitable priming recipe, the pressure was raised from 50 ksi to 120 ksi in steps, resulting in slight, permanent plastic deformation of the chamber and inducing a favorable state of residual stress (autofrettage). The assembly was nondestructively examined for cracks before and after the proof-test procedure, and no reportable indications were found. This report briefly describes the hardware, the rationale behind the proof-test, the mechanical response of the system, the interior ballistics, and the results. Extensive instrumentation was used during the tests, and the results are tabulated and plotted.

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